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East–west differences in water mass, nutrient, and chlorophyll *a* distributions in the sea ice reduction region of the western Arctic Ocean

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[1] The *R/V* Mirai conducted hydrographic surveys in the western Arctic Ocean during summer 2004 across a front between cold Arctic water and warm water from the Pacific Ocean where sea ice cover has been largely reduced in recent summers. The hydrographic data indicate a new type of vertical temperature minimum water west of the front along isohaline surfaces with approximate salinity (S) of 32, which is fresher than the typical temperature minimum ($S \approx 33$) caused by spreading of Pacific winter water (PWW) mainly to the east of the front. Both of the temperature minimum waters are characterized by low potential vorticity with near-freezing temperature, suggesting that they are formed by winter convection with sea ice formation. A difference between the waters results from a large contribution of sea ice meltwater to the fresh temperature minimum (frTmin) water of $S \approx 32$. The distributions of the sea ice meltwater contribution and nitrogen deficit suggest that summer shelf water, largely influenced by the sea ice melt in the Chukchi Sea, is modified by winter convection on its way to the Chukchi Abyssal Plain to form the frTmin water. This water supplies nutrients through the water distribution to the west of the front at depths shallower than the nutrient maximum layer caused by the PWW spreading. The shallower nutrient supply by the frTmin water combined with light penetration without sea ice cover could produce a prominent chlorophyll *a* maximum layer west of the front.

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1. Introduction

[2] Since the late 1990s, catastrophic sea ice reduction during summer has been observed in the Pacific sector of the Arctic Ocean (western Arctic Ocean), and the spatial pattern of this ice reduction has been well correlated with the spatial distribution of warm water from the Pacific Ocean [*Shimada et al.*, 2006]. This warm water, which passes through the Bering Strait and the Chukchi Sea in summer and is called Pacific summer water (PSW), is carried into the Arctic Ocean by the Beaufort Gyre, a basin-scale anticyclonic ocean circulation [*Coachman and Barnes*, 1961]. The northward branch of the Beaufort Gyre flows along the Chukchi Plateau and the Northwind Ridge (Figure 1), resulting in the large summer reduction in sea ice in these areas [*Shimada et al.*, 2001, 2006]. The Chukchi Plateau forms the western boundary of the Beaufort Gyre, and PSW is found east of the Chukchi Plateau [*Shimada et al.*, 2001]. In contrast, water colder than PSW (cold Arctic water) occurs west of the Chukchi Plateau, where the topography consists of a subbasin of the Canada Basin called the Chukchi Abyssal Plain and its western border called the Mendeleyev Ridge. There is little information about the distribution, origins, and formation processes of water masses over the Chukchi Abyssal Plain because of the lack of hydrographic observations. Regions with decreasing sea ice such as in the front between PSW and cold Arctic water might also experience increased biological production compared to the ice-covered ocean because of the intensification of light in the water column [*Lee and Whitledge*, 2005] and greater wind-induced mixing to replenish sea surface nutrients [e.g., *Carmack et al.*, 2006]. In addition, the differences in water masses on both sides of the front over the Chukchi Plateau would control the distributions of nutrients and biological parameters, which could provide insight into spatial biological responses to reductions in sea ice, but this has not been studied. Thus, we examined the water mass distribution and its relationship to the distributions of nutrients and algal biomass (chlorophyll *a*) on both sides of the front over the Chukchi Plateau.

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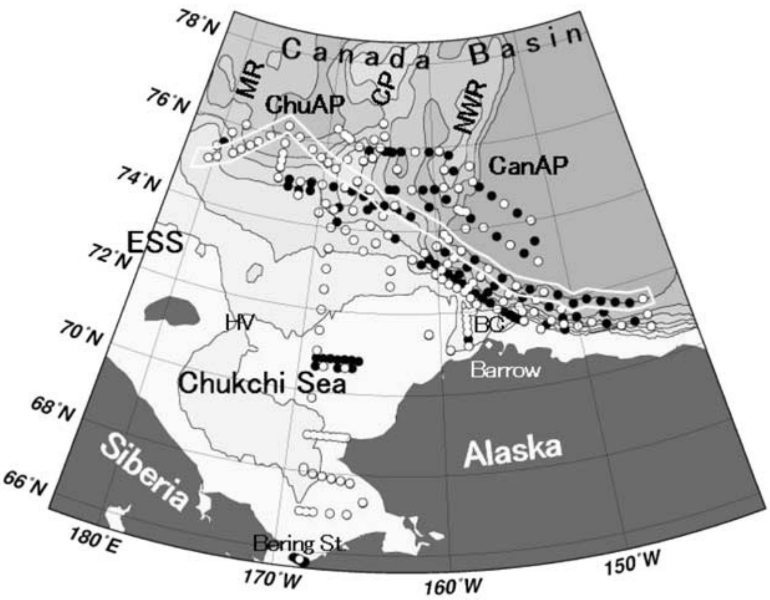

Figure 1. Map showing bathymetric features of the study area and locations of hydrographic stations of the *R*/*V* Mirai Arctic Ocean cruise in 2004. Open circles indicate CTD and hydrographic water sampling stations; closed circles indicate CTD observation stations. The stations enclosed by the white line were used to illustrate the vertical sections shown in Figures 3, 4, 6, 9, 10, and 12. East of the Northwind Ridge (in the Canada Abyssal Plain) the stations used for the illustration were along an isobath of 3000 m. Geographical locations are abbreviated as follows: ESS, East Siberian Sea; MR, Mendeleyev Ridge; ChuAP, Chukchi Abyssal Plain; CP, Chukchi Plateau; NWR, Northwind Ridge; CanAP, Canada Abyssal Plain; BC, Barrow Canyon; HV, Herald Valley.

[3] The vertical structure of water masses over the Canada Basin east of the Chukchi Plateau is recognized as a typical stratification structure in the western Arctic Ocean. Seasonal modification on the Chukchi Sea shelf produces two types of Pacific water, i.e., PSW and Pacific winter water (PWW), which compose the upper part of the western Arctic Ocean (depth < ~200 m) and are characterized by a temperature maximum (salinity [S] = 31–32; depth < ~80 m) and a temperature minimum ($S \approx 33$; depth = 100–150 m), respectively [*Coachman and Barnes*, 1961]. More specifically, on the Chukchi Sea shelf, PSW is further classified into two waters: Alaskan Coastal Water, which has higher temperature and lower salinity and is carried by a current along the Alaskan coast; and Bering Sea Water, which has lower temperature and higher salinity and occupies the bulk of the central Chukchi Sea [*Coachman et al.*, 1975]. *Shimada et al.* [2001] called the former eastern Chukchi summer water (ECSW) and the latter western Chukchi summer water (WCSW); we use this nomenclature to clarify in which season the waters pass through the Chukchi Sea shelf area. The abovementioned PSW that is carried into the Canada Basin by the Beaufort Gyre and forms the temperature maximum at S = 31–32 east of the Chukchi Plateau is strictly the eastern branch of PSW, i.e., ECSW. In contrast, WCSW is assumed to spread into the Chukchi Abyssal Plain and to form a temperature maximum at $S \approx 32.5$ [*Shimada et al.*, 2001; *Steele et al.*, 2004]. However, this connection between WCSW on the Chukchi Sea shelf and the temperature maximum at $S \approx 32.5$ over the Chukchi Abyssal Plain is not clearly evident. Below the upper halocline composed of the Pacific water lies the lower halocline water ($S \approx 34.2$), which is derived from shelves of the Atlantic sector of the Arctic Ocean (eastern Arctic Ocean) [*Aagaard et al.*, 1981; *Jones and Anderson*, 1986]. Deeper still, areas below the lower halocline water are occupied by warm water that originated in the Atlantic Ocean (Atlantic water) and has a temperature maximum at 300–500 m depths in the Canada Basin.

[4] In the context of nutrient supply and biological activity, a plume of nutrients from the Gulf of Anadyr moves into the southwestern Chukchi Sea via the Bering Strait in summer, creating one of the most biologically productive regions in the world ocean [*Walsh et al.*, 1989; *McRoy*, 1993]. Along shelf slopes of the Chukchi and Beaufort seas, nutrient supply from the subsurface nutricline is important for biological production; for example, wind-induced upwellings of subsurface water with abundant nutrients occur over Barrow Canyon [*Hill and Cota*, 2005] and Kugmallit Canyon [*Carmack et al.*, 2004], resulting in extremely high biological production equivalent to that in the shelf region. Furthermore, in the central Canada Basin away from the shelf slope, sea surface nutrient concentrations in summer were decreased from winter concentrations because of biological production at the Surface Heat Budget of the Arctic Ocean/Joint Ice Ocean Study (SHEBA/JOIS) ice camp in 1997–1998 [*McLaughlin et al.*, 2004]. However, few studies have investigated the relationship between the spatial distributions of nutrients and biological activity in the Canada Basin, especially extending to the west of the Chukchi Plateau.

[5] Modern hydrographic observations, including chemical and biological surveys, were conducted across the

Chukchi Abyssal Plain as part of the Larsen 93 expeditions by the Canadian Coast Guard Ship (CCGS) *Henry Larsen* during summer 1993 [*Carmack et al.*, 1995; *McLaughlin et al.*, 1996] and the Arctic Ocean Section 94 (AOS94) research carried out aboard U.S. and Canadian icebreakers during summer 1994 [*Carmack et al.*, 1997; *Swift et al.*, 1997]. These expeditions focused not on the frontal structure over the Chukchi Plateau and the PSW circulation, but on the Pacific/Atlantic front, which is characterized by the presence or absence of PWW, and the Atlantic water circulation. Hydrographic studies based on these data have revealed the shift of the Pacific/Atlantic front toward the Pacific side [*McLaughlin et al.*, 1996, 2002] and a warm temperature anomaly carried by the Atlantic water circulation [*Carmack et al.*, 1995, 1997]. However, it is difficult to ascertain the frontal structure over the Chukchi Plateau using the Larsen 93 data because observations were spatially sparse, with only one or two stations in each subbasin. Moreover, the hydrographic section of AOS94 in the Pacific side was from the Chukchi Sea shelf to the North Pole via the Chukchi Abyssal Plain. Therefore, the section data did not include east–west water mass distributions across the Chukchi Plateau.

[6] In summer 2004, the *R/V* Mirai of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) conducted hydrographic surveys in open water of the Canada Basin with wide east–west ranges from the shelf slope of the East Siberian Sea to the Chukchi Abyssal Plain, where no modern hydrographic sections have previously been available, and from the Chukchi Plateau to the Canada Abyssal Plain (Figure 1). The collected data are described in section 2. In section 3, we discuss the water mass distribution obtained from the surveys, focusing on the distribution over the Chukchi Abyssal Plain that differs from typical views and presenting a new type of vertical temperature minimum water of $S \approx 32$ (section 3.1). We further examine the PWW ($S \approx 33$) and its frontal structure over the Chukchi Plateau (section 3.2), as well as the relationship between WCSW on the Chukchi Sea shelf and the temperature maximum at $S \approx 32.5$ over the Chukchi Abyssal Plain (section 3.3). In addition, we associate the nutrient and chlorophyll *a* distributions with the water mass distribution (section 3.4). In section 4, we examine the new type of temperature minimum water and investigate the most likely formation process and the contribution of greater nutrient availability to biological activity over the Chukchi Abyssal Plain. In section 5, we summarize and discuss our results.

2. Data

[7] During the cruise of *R/V* Mirai from 1 September to 12 October 2004, a conductivity-temperature-depth (CTD) system (Sea-Bird Electronics Inc., SBE9plus) and a Carousel water sampling system with 36 Niskin bottles (12 L) were used for the hydrographic surveys. The precisions of temperature and salinity acquired from the CTD system were 0.0001°C and 0.0006 psu, respectively. The CTD-salinity was calibrated by comparison with bottled seawater salinity analyzed using a Guildline AUTOSAL salinometer. Total alkalinity, which was used to calculate the fractions of freshwater as described below, was measured onboard the ship by potentiometry; the precision was 1.68 μmol/kg.

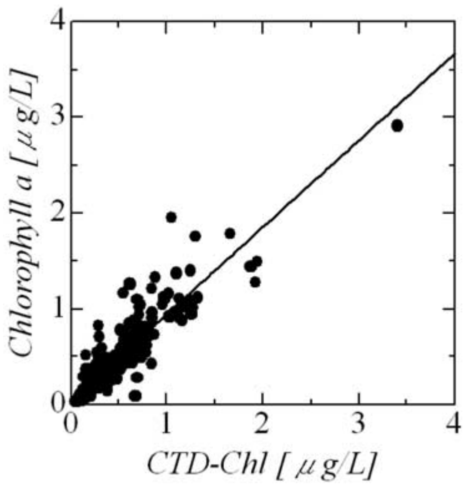

Figure 2. Relationship between sampled water chlorophyll *a* and chlorophyll *a* measured by a fluorometer attached to a CTD system (CTD-Chl). The relation is as follows: chlorophyll *a* = 0.90(CTD-Chl) + 0.04, with an error of 0.18 μg/L (r = 0.90).

Nutrient analyses were also performed onboard using BRAN + LUEBBE TRAACS 800 systems. The coefficients of variation (CVs) for phosphate, silicate, nitrate, nitrite, and ammonium at each station were less than 0.28, 0.18, 0.19, 0.31, and 0.98%, respectively. Further details are provided in the *R/V* Mirai 2004 cruise report [*Shimada*, 2004]. Chlorophyll *a* in water samples (n = 211) was measured using a fluorometric nonacidification method [*Welschmeyer*, 1994] and a Turner Design fluorometer (10-AU-005). A fluorometer (Seapoint Sensors, Inc.) attached to the CTD system also determined the chlorophyll *a* concentration (CTD-Chl). There was a strong positive correlation between the sampled water chlorophyll *a* and CTD-Chl, such that chlorophyll *a* = 0.90(CTD-Chl) + 0.04 with an error of 0.18 (μg/L) and a correlation coefficient (r) of 0.90 (n = 206; Figure 2). Note that five measurements of the sampled water chlorophyll *a* were eliminated because the differences in concentration between the two methods were more than three times the standard deviation of the concentration difference.

3. Results

[8] To examine the water mass distribution, we studied the vertical section of temperature with salinity contours from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east (Figure 3). The salinity contours represent isohaline surfaces and nearly correspond to isopycnal surfaces because density at low temperatures strongly depends on salinity. The temperature layering structure differs east and west of the Chukchi Plateau. East of the Chukchi Plateau, warm surface water occurs at $S < 32$, whereas temperature minimum water lies along isohaline surfaces of approximately $S = 33$. The former is ECSW that has passed through the Bering Strait and along the Alaskan coast in summer [*Coachman and Barnes*, 1961; *Shimada et al.*, 2001]. The latter is typical PWW that has passed through the Bering Strait and the Chukchi Sea in winter

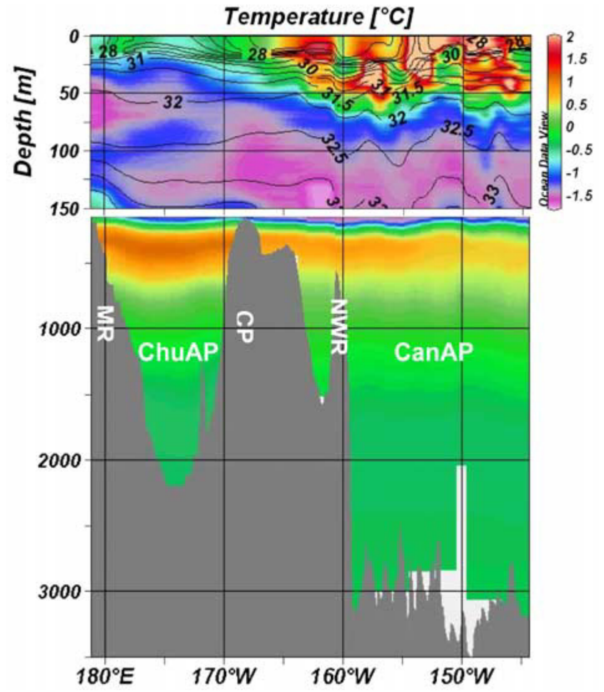

Figure 3. Vertical section of temperature from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. Contours indicate salinity. Geographical locations are abbreviated as follows: MR, Mendeleyev Ridge; ChuAP, Chukchi Abyssal Plain; CP, Chukchi Plateau; NWR, Northwind Ridge; CanAP, Canada Abyssal Plain.

[*Coachman and Barnes*, 1961]. West of the Chukchi Plateau, the layering structure is more complicated. Two temperature minima occur at $S \approx 32$ and 33; between these minima is a temperature maximum at $S \approx 32.5$, which is more saline than ECSW. We refer to this maximum as the saline temperature maximum (salTmax). The salTmax water at $S \approx 32.5$ is thought to originate in WCSW on the Chukchi Sea shelf in summer [*Shimada et al.*, 2001; *Steele et al.*, 2004]. The temperature minimum at $S \approx 33$ below salTmax is associated with PWW. We refer to the temperature minimum at $S \approx 32$, which is fresher than PWW, as the fresh temperature minimum (frTmin). This water mass has not been studied previously. Therefore, we first focused on this water and examined its properties (section 3.1), followed by the salTmax water and PWW. Below PWW, a temperature maximum occurs at 300–500 m depths and has characteristics of the Atlantic water. Here, we concentrate on the water temperature, salinity, and chemical properties of the upper ocean above PWW (0–150 m) for the Chukchi Abyssal Plain and the Canada Abyssal Plain (Table 1).

3.1. Fresh Temperature Minimum Water

[9] It is difficult to examine the difference in temperature minimum waters between $S \approx 32$ and 33 from the temperature distribution alone. Useful information to distinguish the waters is derived from freshwater distributions. We calculated the fractions of sea ice meltwater (f_{SIM}) and other freshwater (f_{OF}) from the relationship of total alkalinity and salinity based on the analysis by *Yamamoto-Kawai et al.* [2005]. The fraction of sea ice meltwater, f_{SIM}, increases when seawater is influenced by sea ice melt in summer and decreases when seawater is influenced by sea ice formation in winter. A negative f_{SIM} implies that sea ice formation, which removes freshwater from and ejects brine into seawater, is dominant over sea ice melt. The fraction of other freshwater, f_{OF}, comprises river runoff, precipitation, and freshwater carried by the Pacific water (PSW and PWW), which has lower salinity than the Atlantic water.

[10] We examined the distributions of f_{SIM} and f_{OF} from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east (Figure 4). The distribution of f_{SIM} (Figure 4a) differs greatly between the east and west of the Chukchi Plateau. Although sea ice meltwater ($f_{SIM} > 0$) occurs in the upper 20 m in both regions, only over the Chukchi Abyssal Plain is there a prominent maximum f_{SIM} (≈ 0) at depths between 50 and 75 m (approximately $S = 32$). This coincides with the frTmin layer. The f_{OF} generally increases with decreasing depth (Figure 4b). However, over the Chukchi Abyssal Plain, f_{OF} is almost constant from $S \approx 33$ to $S \approx 32$, whereas f_{SIM} sharply increases with decreasing depth such that the vertical gradient of f_{SIM} is one order of magnitude larger than that of f_{OF}. This means that the excess freshwater contained in the frTmin water ($S \approx 32$) relative to PWW ($S \approx 33$) is mainly related to the increase in f_{SIM}.

[11] The coincidence of frTmin with the f_{SIM} maximum at $S \approx 32$ over the Chukchi Abyssal Plain sheds light on the formation process of this water. The frTmin water has near-freezing temperature, suggesting an influence of sea ice formation. Sea ice formation accompanies brine rejection and decreases the f_{SIM}. However, the f_{SIM} in the frTmin layer is higher than that in surrounding layers. This higher f_{SIM} indicates a contribution of sea ice melt that largely offsets the influence of sea ice formation. In other words, water containing sea ice meltwater, which is input in summer, loses heat and gains salt in association with sea ice formation in winter, resulting in the formation of water with near-freezing temperature (frTmin) and $f_{SIM} \approx 0$. We provide a more detailed discussion of the formation process of frTmin water in section 4.

Table 1. Variety of Temperature Minima and Maxima, Their Salinities, and the Corresponding Chemical Properties Over the Chukchi Abyssal Plain and the Canada Abyssal Plain

Chukchi Abyssal Plain			Canada Abyssal Plain		
Temperature	Salinity	Chemical	Temperature	Salinity	Chemical
frTmin[a]	≈32	f_{SIM} max[b]	ECSW-Tmax[c]	31–32	Ammonium max[d]
SalTmax[e]	≈32.5	N** min[f]			
PWW-Tmin[g]	≈33	Nutrient max[h]	PWW-Tmin[g]	≈33	Nutrient max[h]

[a]Temperature minimum fresher than Pacific winter water (PWW).
[b]Maximum of the sea ice meltwater fraction associated with frTmin water.
[c]Temperature maximum associated with eastern Chukchi summer water (ECSW).
[d]Ammonium maximum imprinted at the base of ECSW.
[e]Temperature maximum saltier than ECSW.
[f]Minimum of N** between frTmin water and PWW.
[g]Temperature minimum associated with PWW.
[h]Nutrient maximum associated with PWW.

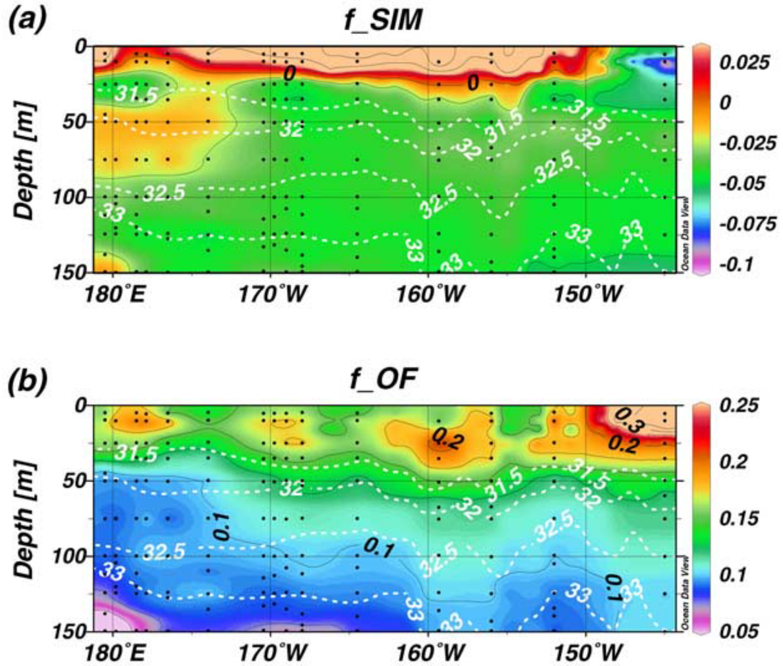

Figure 4. Vertical sections of the (a) fraction of sea ice meltwater (f_{SIM}) and (b) fraction of other freshwater (f_{OF}) from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. At each station, the data sampling levels are indicated by black dots. In Figure 4a, f_{SIM} contours are from -0.075 to 0.075 and the contour interval is 0.025. In Figure 4b), f_{OF} contours are from 0.05 to 0.3 and the contour interval is 0.025. White dotted lines indicate salinity contours of 31.5, 32, 32.5, and 33.

[12] To examine the horizontal distribution of frTmin water, we illustrated the distribution of temperature on the isohaline surface of $S = 32$ (Figure 5a). The temperature is the lowest at the southwestern corner of the Chukchi Abyssal Plain, and a tongue of low temperature corresponding to the frTmin water spreads throughout the Chukchi Abyssal Plain. The temperature increases east of the Chukchi Plateau and further increases east of the Northwind Ridge along the Beaufort Sea shelf slope. According to *Shimada et al.* [2001], the isohaline surface of $S = 32$ is located at the bottom of ECSW, and the water is carried by the Beaufort Gyre with the northward flows along the Northwind Ridge and the Chukchi Plateau. The higher temperature east of the Chukchi Plateau is consistent with the distribution of ECSW carried by the Beaufort Gyre. Thus, the Chukchi Plateau is a boundary between ECSW from the east and frTmin water from the west.

[13] The ECSW and frTmin water differ in freshwater content, which is indicated in the distribution of f_{OF} on the $S = 32$ surface (Figure 5b). Higher f_{OF} occurs east, and lower f_{OF} occurs west, of the Chukchi Plateau. The main components of f_{OF} are river runoff and freshwater carried by the Pacific water because precipitation is smaller than other components in the Arctic Ocean [*Aagaard and Carmack*, 1989; *Schlosser et al.*, 2002; *Yamamoto-Kawai et al.*, 2005]. Therefore, ECSW spreading east of the Chukchi Plateau contains a large amount of river runoff and freshwater from the Pacific. This is consistent with an earlier report [*Coachman et al.*, 1975] and a more recent analysis of barium (Ba) as a tracer for river water [*Guay and Falkner*, 1997]. West of the Chukchi Plateau, the lack of f_{OF} (salinity excess) on the isohaline surface of frTmin is compensated by the sea ice meltwater contribution (salinity deficit), as described above.

[14] On the basis of studies by *Aagaard and Carmack* [1989] and *Proshutinsky et al.* [2002], the Canada Basin is a reservoir of freshwater because the convergence of Ekman transport caused by the anticyclonic sea ice motion accumulates the surface freshwater. In addition to the Ekman pumping, freshwater is carried into the Canada Basin by the Beaufort Gyre, the scale of which is smaller than that of the anticyclonic sea ice motion and is restricted to the east of the Chukchi Plateau [*Shimada et al.*, 2001], governed by dynamics associated with the bottom topography [*Sumata and Shimada*, 2007]. Our analysis indicates that the freshwater content differs inside and outside the Beaufort Gyre. Inside the gyre, there is a reservoir of river runoff and freshwater from the Pacific, whereas outside the gyre, there is a reservoir of sea ice meltwater in the frTmin layer over the Chukchi Abyssal Plain.

3.2. Pacific Winter Water

[15] A characteristic of PWW is its low potential vorticity associated with a large volumetric injection of the water formed by winter convection [*Shimada et al.*, 2005]. To understand the volumetric injection of waters to the Canada Basin, we examined the distribution of potential vorticity from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east (Figure 6). East of the Chukchi Plateau, low potential vorticity occurs just above $S = 33$, where the temperature is at its vertical minimum. This

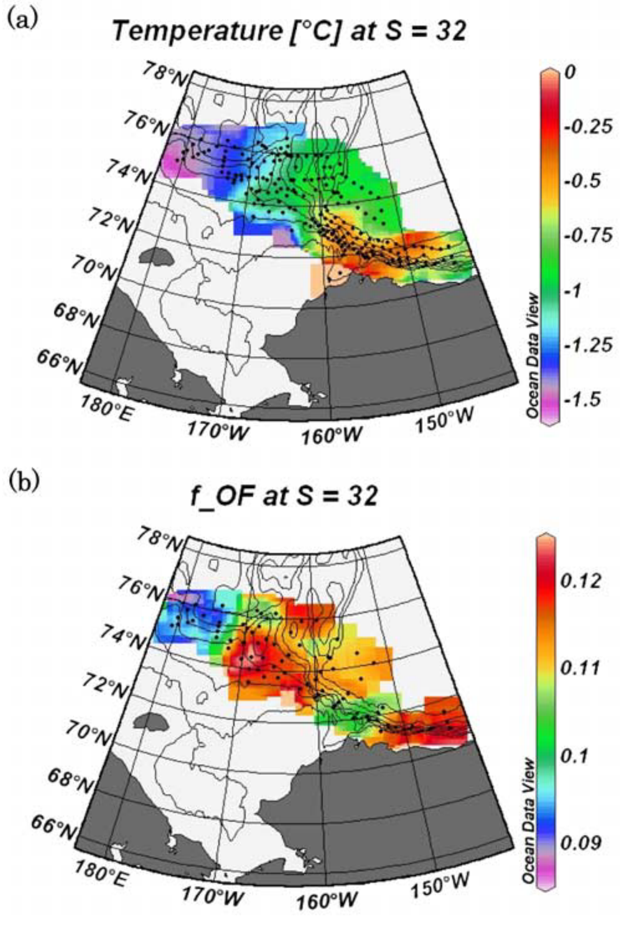

Figure 5. (a) Temperature and (b) fraction of other freshwater (f_{OF}) at a surface of salinity of 32. Data from the Chukchi Sea Shelf (bottom depth <100 m) are excluded.

indicates that PWW, which is formed by winter convection over the northern Bering and Chukchi sea shelves [*Aagaard et al.*, 1981, 1985; *Schumacher et al.*, 1983; *Cavalieri and Martin*, 1994], spreads into the Canada Basin mainly east of the Chukchi Plateau. We also found a temperature minimum at $S \approx 33$ west of the Chukchi Plateau, but the potential vorticity of this water is much higher than that of the temperature minimum east of the Chukchi Plateau. That is, the volumetric injection of PWW is much smaller to the west of the Chukchi Plateau compared with that to the east. We found another potential vorticity low at $S \approx 32$ west of the Chukchi Plateau in the frTmin water. The near-freezing temperature and low potential vorticity there suggest that the frTmin water is also formed by winter convection.

[16] To examine the horizontal distribution of PWW and its modification, we illustrated the distributions of temperature and potential vorticity on the isohaline surface of $S = 33$ (Figure 7). There is a front over the Chukchi Plateau between water with lower temperature and potential vorticity in the east and water with higher temperature and potential vorticity in the west. The lowest temperature and potential vorticity occur along the Chukchi Sea shelf slope between the Chukchi Plateau and the Northwind Ridge. This water is likely carried by the Beaufort Gyre into the basin interior east of the Chukchi Plateau, resulting in the lower temperature and potential vorticity there. In contrast, west of the Chukchi Plateau, the highest temperature and potential vorticity occur at the southwestern corner of the Chukchi Abyssal Plain. There, the isohaline surfaces below $S = 33$ become shallow toward the shelf (Figure 3), suggesting the upwelling of warm lower halocline water to the PWW layer over the shelf slope [*Woodgate et al.*, 2005]. The upwelling narrows the vertical interval of isohaline surfaces at $S \approx 33$, resulting in high potential vorticity. In the interior of the Chukchi Abyssal Plain, the temperature and potential vorticity are intermediate to those at the southwestern corner and east of the Chukchi Plateau. Therefore, the water there is influenced by both typical PWW leaked from east of the Chukchi Plateau and lower halocline water upwelled over the shelf slope.

3.3. Saline Temperature Maximum Water

[17] The salTmax water at $S \approx 32.5$ over the Chukchi Abyssal Plain is thought to originate in WCSW on the Chukchi Sea shelf in summer [*Shimada et al.*, 2001; *Steele et al.*, 2004]. The potential vorticity of WCSW above the bottom of the Chukchi Sea shelf (data not shown) is as low as that of frTmin water and PWW. The low potential vorticity of WCSW is likely caused by tidal mixing on the shelf [*Padman*, 1995; *Woodgate et al.*, 2005]. In

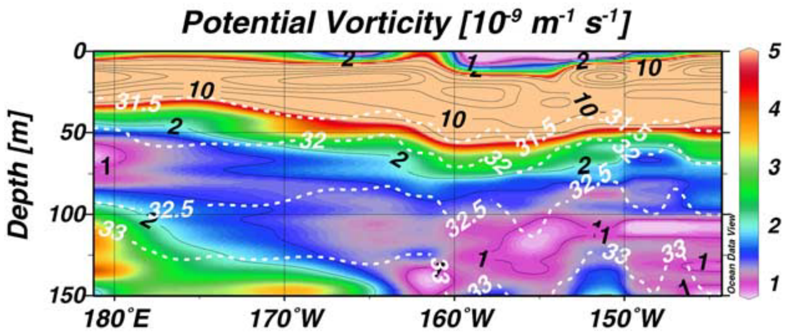

Figure 6. Vertical section of potential vorticity from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. The contour units are 10^{-9} m^{-1} s^{-1}; the contour intervals are 0.5×10^{-9} m^{-1} s^{-1} from 1 to 2×10^{-9} m^{-1} s^{-1} and 4×10^{-9} m^{-1} s^{-1} from 2 to 22×10^{-9} m^{-1} s^{-1}. White dotted lines indicate salinity contours of 31.5, 32, 32.5, and 33.

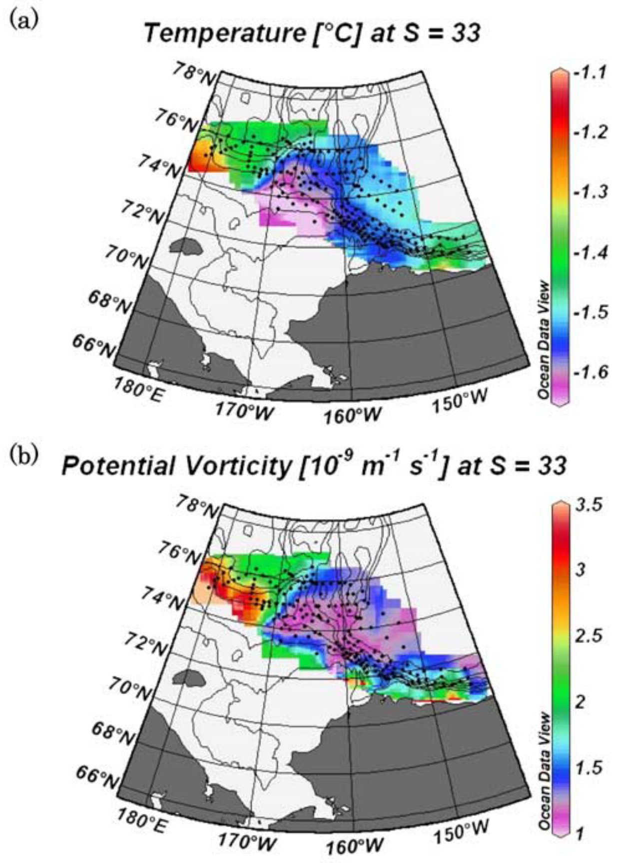

Figure 7. (a) Temperature and (b) potential vorticity at a surface of salinity of 33. Data from the Chukchi Sea Shelf (bottom depth <100 m) are excluded.

contrast, the potential vorticity of salTmax water over the Chukchi Abyssal Plain is higher than that of frTmin water and PWW, which are formed by volumetric water injection (Figure 6). This implies that salTmax is not formed by a volumetric injection of WCSW.

[18] Additional evidence that WCSW is not a large component of salTmax water is derived from the relationship between temperature and salinity (*TS* relation; Figure 8). Warm water (>2°C) at $S \approx 32.5$ is found east of the Herald Valley, where WCSW extends eastward along the bathymetry via the valley [*Coachman et al.*, 1975; *Weingartner et al.*, 2005]. At the entrance of the Canada Basin, the *TS* relation is typical for the western Arctic, with the temperature minimum of PWW at $S \approx 33$. Between the two stations, the *TS* relation indicates a zigzag structure between the two end-member envelopes of WCSW and PWW, reflecting the encounter of WCSW and PWW, which causes double diffusive interleaving [e.g., *May and Kelley*, 2001]. Therefore, WCSW is largely modified by PWW north of the Herald Valley. The *TS* relation in the southwestern Chukchi Abyssal Plain, where the temperature at $S = 32.5$ (salTmax) is highest within the abyssal plain, shows that this highest temperature is much lower than the average temperature of the zigzag structure at $S \approx 32.5$ just north of the Herald Valley, where WCSW is largely modified. The temperature of salTmax water is similar to that of frTmin water and PWW, suggesting large contributions of these waters, rather than WCSW. In addition, the potential vorticity is relatively high at the salTmax. We thus propose that the salTmax represents not a substantial water mass, but a passive boundary determined by the existence of the two temperature minima of frTmin water and PWW. The contribution of WCSW is likely small north of the Herald Valley. Therefore, although salTmax might be a remnant of WCSW, it is largely modified by mixing with the frTmin water above and PWW below.

[19] The proposal that salTmax is only a vertical boundary between the two temperature minimum waters is also supported by the chemical tracer N** = 0.87 ($[NO_3^-]$ + $[NO_2^-]$ + $[NH_4^+]$ − $16[PO_4^{3-}]$ + 2.9) (μmol/kg), defined by *Codispoti et al.* [2005]. At the bottom of a shelf, nitrate and nitrite are used instead of oxygen for the decomposition of organic matter and are removed as free nitrogen gas from the water column via denitrification, resulting in a nitrogen deficit relative to phosphate [e.g., *Devol et al.*, 1997]. Because of the nitrogen deficit, N** is negative at the bottom of the shelf. As *Codispoti et al.* [2005] indicated, negative N** occurs in the Canada Abyssal Plain as a result of the spreading of shelf water that has been in contact with the bottom of the Chukchi Sea (Figure 9). Our observation area extended to the Chukchi Abyssal Plain, and we found an N** minimum along isohaline surfaces of $S \approx 32.5$; this minimum is prominent compared with that in the Canada Abyssal Plain. The N** minimum corresponds to salTmax. Therefore, salTmax is located at the bottom of the shelf water or at the vertical boundary of the shelf and deeper waters. The shelf water just above the N** minimum is largely composed of the frTmin water, whereas the deeper water just below the N** minimum is PWW influenced by the lower halocline water, as described in section 3.2.

3.4. Nutrient and Chlorophyll *a* Distributions

[20] We examined nutrient and chlorophyll *a* distributions by comparing the water mass distribution described above. The distribution of silicate (Figure 10a) is representative of the distributions of other nutrients (data not shown). The silicate concentration at the sea surface is very low (<10 μmol/kg) because of biological uptake. The concentration increases with depth and reaches a vertical maximum (≈35 μmol/kg) at $S \approx 33$. The silicate (nutrient) maximum coincides with the temperature minimum of PWW at $S \approx 33$ because PWW originally has abundant nutrients and further increases the concentration during the transition across the Chukchi Sea shelf, where regenerated nutrients are released from the bottom [*Kinney et al.*, 1970; *Moore et al.*, 1983; *Jones and Anderson*, 1986]. Focusing on the silicate concentration at $S = 32$, where the frTmin water lies west of the Chukchi Plateau and ECSW lies east of it, the concentration is higher to the west than to the east. That is, the frTmin water has higher nutrient contents than does ECSW.

[21] There is a subsurface chlorophyll *a* maximum (Figure 10b). In general, this subsurface chlorophyll *a* maximum over the southern Canada Basin occurs at the nutricline near the base of the euphotic zone as a signal of postblooming [e.g., *Cota et al.*, 1996; *Carmack et al.*, 2004]. The chlorophyll *a* distribution also exhibits an east–west contrast. The vertical chlorophyll *a* maximum

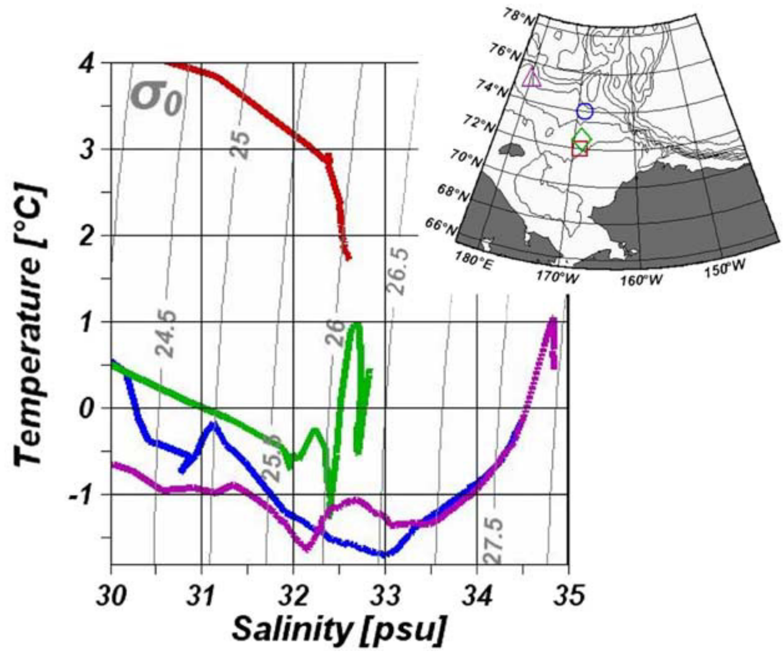

Figure 8. The relation between temperature and salinity measured at stations in the Chukchi Sea and the Chukchi Abyssal Plain. The colors of profiles correspond to those of the stations: red is for east of the Herald Valley, blue is for entrance of the Canada Basin, green is for between the Herald Valley and the Canada Basin, and purple is for southwestern Chukchi Abyssal Plain. Gray solid lines indicate potential density (σ_0) contours determined using the equation of state (EOS80) suggested by *Millero et al.* [1980].

is most prominent over the Chukchi Abyssal Plain. It lies along isohaline surfaces at $S \approx 31.5$, which is just above the temperature minimum of frTmin water at $S \approx 32$ where nutrients are relatively abundant. Therefore, the frTmin water presumably plays an important role in nutrient supply to the chlorophyll *a* maximum.

[22] We examined horizontal nutrient distributions in terms of water masses and relationships to total chlorophyll *a* in the water column (Figure 11). The layer from the sea surface to $S = 32.5$ contains frTmin water ($S \approx 32$) west of the Chukchi Plateau and ECSW ($S = 31-32$) east of it (Figure 11a); the layer above $S = 33.5$ additionally contains PWW with the nutrient maximum ($S \approx 33$; Figure 11b). In the former layer, the amount of silicate is larger to the west of the Chukchi Plateau than to the east (Figure 11a). The distribution of the larger amount of silicate is associated with the frTmin water distribution, whereas that of the smaller amount of silicate is associated with the ECSW distribution. In contrast, in the latter layer, high silicate content occurs in the Canada Abyssal Plain (Figure 11b). Because the major nutrient provider to the western Arctic Ocean is PWW [*Kinney et al.*, 1970; *Moore et al.*, 1983; *Jones and Anderson*, 1986], the high silicate content in the Canada Abyssal Plain is consistent with a large contribution of PWW.

[23] Total chlorophyll *a* was obtained by the vertical integration of chlorophyll *a* over the water column (Figure 11c). The integration was performed for chlorophyll

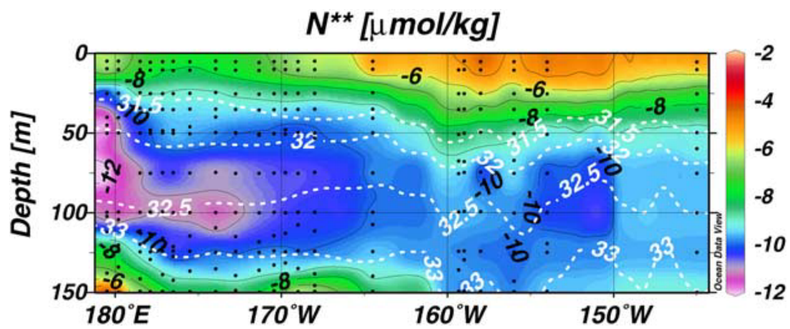

Figure 9. Vertical section of N** from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. At each station, data sampling levels are indicated by black dots. The N** contours are from -12 to -5 μmol/kg, with an interval of 1 μmol/kg. White dotted lines indicate salinity contours of 31.5, 32, 32.5, and 33.

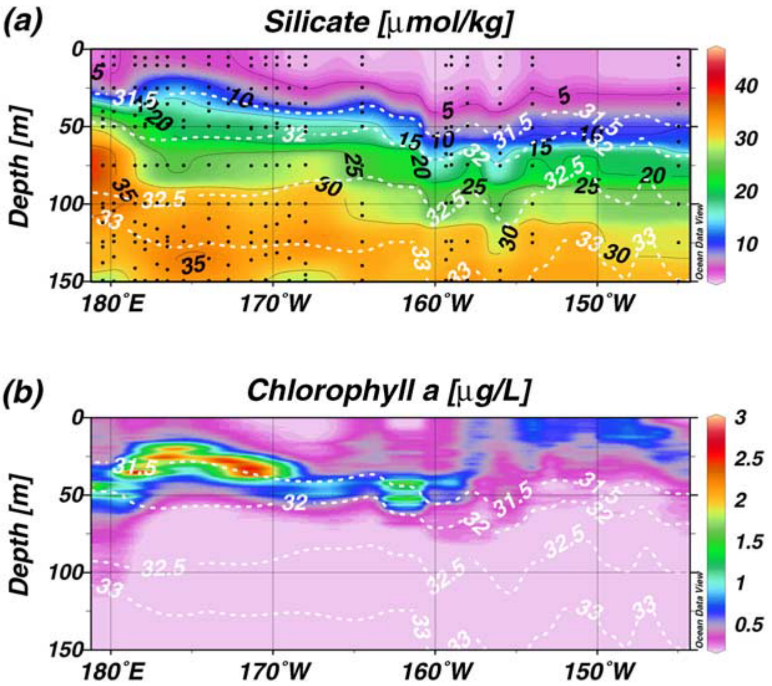

Figure 10. Vertical sections of (a) silicate and (b) chlorophyll *a* from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. At each station, data sampling levels are indicated by black dots. In Figure 10a, the silicate contours are from 5 to 35 μmol/kg, with an interval of 5 μmol/kg. In Figure 10b, the unit of chlorophyll *a* is μg/L. White dotted lines indicate salinity contours of 31.5, 32, 32.5, and 33.

a concentrations >0.18 μg/L (i.e., greater than measurement error). The amount of chlorophyll *a* is larger to the west of the Chukchi Plateau than to the east. This larger amount of chlorophyll *a* is consistent with the higher silicate concentration of frTmin water, but is not related to the PWW contribution as the major nutrient provider.

4. Discussion

[24] This was the first examination of the frTmin water at $S \approx 32$ over the Chukchi Abyssal Plain. The water is characterized by low potential vorticity with near-freezing temperature, suggesting that the water forms by winter convection with sea ice formation. This water and PWW, which is also formed by winter convection over the northern Bering and Chukchi sea shelves [*Aagaard et al.*, 1981, 1985; *Schumacher et al.*, 1983; *Cavalieri and Martin*, 1994], differ in f_{SIM}. The f_{SIM} of frTmin water ($\approx$0) is larger than that of PWW (<0). The larger f_{SIM} of frTmin water results from the contribution of sea ice meltwater input in summer, which largely offsets the effect of brine rejection when the temperature minimum water forms in winter.

[25] Where does the sea ice meltwater input occur? If we assume that the high f_{SIM} at $S = 32$ over the Chukchi Abyssal Plain (Figure 4a) is caused by the vertical transport of sea ice meltwater from the surface across the strong stratification at approximately 20 m (Figure 6), then the f_{OF} there should be high because freshwater other than sea ice meltwater would also be transported from the surface. However, this assumption is inconsistent with the observed distribution of low f_{OF} at $S = 32$ over the Chukchi Abyssal Plain compared with that east of the Chukchi Plateau (Figure 4b). Therefore, the sea ice meltwater at $S = 32$ over the Chukchi Abyssal Plain is not derived vertically from the surface, but horizontally from elsewhere.

[26] The frTmin water has the N** minimum at the bottom, suggesting that this water is derived from shelf regions adjacent to the Chukchi Abyssal Plain. *Mathis et al.* [2007] estimated that the surface sea ice meltwater diffuses down to depths of $S = 32$ or lower in the Chukchi Sea during the summer. In contrast, data obtained from the East Siberian Sea in summer [*Olsson and Anderson*, 1997] indicate that f_{SIM} with $S = 32$ is <-0.1, suggesting a lesser contribution of sea ice meltwater. Thus, the vertical transport of surface sea ice meltwater in the Chukchi Sea would be caused by weak stratification due to high surface salinity compared with that in the East Siberian Sea, where a large freshwater contribution from river runoff induces low surface salinity and strong stratification. Therefore, the f_{SIM} maximum of frTmin water over the Chukchi Abyssal Plain is likely attributable to sea ice meltwater input in the Chukchi Sea. The temperature and f_{SIM} characteristics of summer water in the Chukchi Sea would be modified by sea ice formation in winter on its way to the Chukchi Abyssal Plain to form the frTmin water with $f_{\mathrm{SIM}} \approx 0$.

[27] The spreading of frTmin water into the Chukchi Abyssal Plain along isohaline surfaces of $S \approx 32$ contributes the higher nutrient concentrations observed there compared to concentrations east of the Chukchi Plateau (Figure 10a). There are a number of possible reasons for this east–west

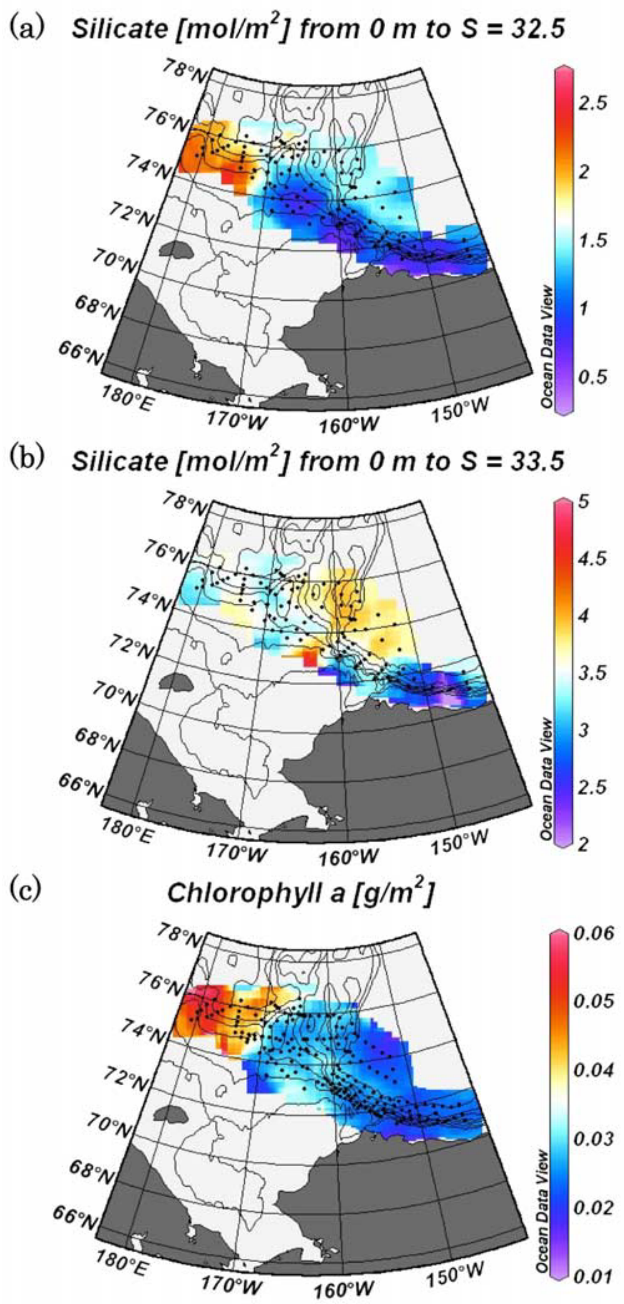

Figure 11. Vertical integration of (a) silicate from the sea surface to an isohaline surface of $S = 32.5$, (b) silicate from the sea surface to an isohaline surface of $S = 33.5$, and (c) chlorophyll *a* in the water column. Data from the Chukchi Sea Shelf (bottom depth <100 m) are excluded. In Figure 11c, the integration was performed for chlorophyll *a* concentrations >0.18 μg/L (i.e., greater than measurement error).

contrast in nutrient concentrations. The N** minimum at the bottom of the frTmin water suggests that the water was in contact with shelf sediments, regenerating the nutrients in the water. The winter convection forming the frTmin water could entrain higher amounts of nutrients from below. Waters within the Beaufort Gyre that occupy areas east of the Chukchi Plateau (ECSW and river water) have a decadal residence time [*Schlosser et al.*, 1995; *Macdonald et al.*, 2004], resulting in the stripping of nutrients from the waters via the sinking of biogenic particles [e.g., *Bates et al.*, 2005]. The higher nutrient contents of frTmin water over the Chukchi Abyssal Plain would maintain the prominent vertical chlorophyll *a* maximum just above the frTmin water (Figure 10b). Indeed, a large amount of nutrients is mainly carried by PWW, and the spreading of this water into the Canada Basin forms the nutrient maximum layer [*Kinney et al.*, 1970; *Moore et al.*, 1983; *Jones and Anderson*, 1986], but the depth of the maximum (100–150 m) is much deeper than the euphotic zone. The frTmin water supplies the nutrients to a shallower depth than the nutrient maximum depth, and these nutrients could be used effectively for biological activity.

[28] Field experiments performed for the western Arctic Shelf–Basin Interactions (SBI) project demonstrated that shelf water with high nutrient availability for biological activity is carried eastward along the Chukchi Sea shelf slope [*Codispoti et al.*, 2005; *Hill and Cota*, 2005]. However, the frTmin water, which has minimum N** at the bottom, high nutrient contents, and is likely derived from the Chukchi Sea shelf, occurs over the Chukchi Abyssal Plain. Therefore, in addition to the eastward nutrient pathway along the Chukchi Sea shelf slope, there should be a northward nutrient pathway from the Chukchi Sea shelf to the Chukchi Abyssal Plain. According to the numerical model of *Winsor and Chapman* [2004], currents around the Chukchi Sea shelf slope are eastward when winds are northerly, southerly, or westerly, or there is no wind. Only when winds are easterly, which occur predominantly in winter, do the currents flow toward the north, and the water in the Chukchi Sea seems to outflow to the Chukchi Abyssal Plain. Therefore, the spreading of frTmin water from the Chukchi Sea shelf to the Chukchi Abyssal Plain might occur in winter.

[29] In addition to the nitrogen deficit signal N**, ammonium is a tracer of shelf water that has been in contact with the bottom of shelf regions. Ammonium is produced by the decomposition of organic matter that is deposited at the bottom of Chukchi Sea shelf in spring and summer when primary production is high [*Cooper et al.*, 1997; *Codispoti et al.*, 2005]. The SBI field experiments indicated that an ammonium maximum, which corresponds to an N** minimum, spreads from the Chukchi Sea shelf to the Canada Basin, suggesting a shelf water plume [*Codispoti et al.*, 2005]. However, the east–west distributions of ammonium (Figure 12) and N** over the Canada Basin that we obtained are quite different from each other. The ammonium maximum occurs east of the Chukchi Plateau along isohaline surfaces at $S \approx 32$. Ammonium is also detected at depths of $S \approx 33$ around 160° W. In contrast, the N** minimum is prominent west of the Chukchi Plateau along the isohaline surfaces at $S \approx 32.5$ (Figure 9). This contrast is thought to occur as a result of the different origins of the N** minimum and ammonium maximum signals.

[30] We suggested that the frTmin water with the N** minimum at the bottom is derived from the Chukchi Sea shelf. The N** is lower in the western than in the eastern Chukchi Sea [*Codispoti et al.*, 1991]. In contrast, the high-

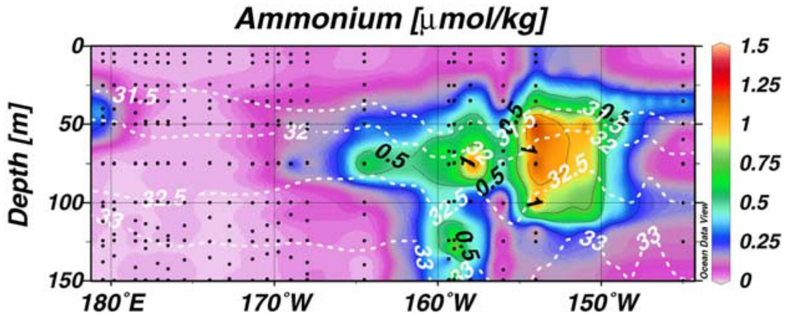

Figure 12. Vertical section of ammonium from the Chukchi Abyssal Plain in the west to the Canada Abyssal Plain in the east. See Figure 1 for the locations of sampling stations. At each station, data sampling levels are indicated by black dots. The ammonium contours are from 0.25 to 1 μmol/kg, with an interval of 0.25 μmol/kg. White dotted lines indicate salinity contours of 31.5, 32, 32.5, and 33.

est ammonium on the isohaline surface of S = 32 occurs near Barrow Canyon (Figure 13). Barrow Canyon is one of the most productive regions because of the upwelling of nutrient-rich water [*Hill and Cota*, 2005]. Therefore, the deposition of organic matter and the production of ammonium at the bottom would be high. Such a high ammonium signal is likely imprinted on the bottom of ECSW ($S \approx 32$) passing through Barrow Canyon. The ammonium distribution east of the Chukchi Plateau is consistent with the distribution of ECSW. Ammonium at depths of $S \approx 33$ around 160° W would be carried by PWW that remained on the shelf even in summer.

[31] East of the Chukchi Plateau, the surface layer nutrient concentrations are extremely low (Figure 10a) because of the influences of nutrient-stripped ECSW and river water. These nutrient-poor waters overlie the nutrient-rich PWW, resulting in low biological activity. The Chukchi Abyssal Plain, which is located on the shallow nutrient pathway to the central Arctic with the spreading of frTmin water, is likely a region where biological activity increases dramatically when the sea ice disappears in summer. The total chlorophyll *a* integrated over the water column over the Chukchi Abyssal Plain south of the ice edge in summer 2004 was >50 mg/m^2 (Figure 11c), which is at least two times greater than that in summer 1994 ($\approx$25 mg/m^2), when sea ice covered this area [*Gosselin et al.*, 1997].

5. Summary

[32] The distribution of waters in the upper ocean of the western Arctic has been studied in terms of PSW and PWW, which are characterized by a temperature maximum lying between S of approximately 31 and 32 and a temperature minimum at $S \approx 33$ corresponding to a nutrient maximum, respectively [*Coachman and Barnes*, 1961; *Kinney et al.*, 1970]. Such a typical water distribution occurs east of the Chukchi Plateau. However, west of the Chukchi Plateau, the distribution is not typical; there are two temperature minima at $S \approx 32$ and 33, within which lies a temperature maximum along isohaline surfaces at $S \approx 32.5$.

[33] The $S \approx 32$ temperature minimum (frTmin) water over the Chukchi Abyssal Plain is also characterized by a $f_{\rm SIM}$ maximum, suggesting a contribution of sea ice meltwater. We conjecture that the sea ice meltwater is supplied vertically in summer from the surface of the Chukchi Sea, where stratification is weak compared with that in the Canada Basin, and the East Siberian Sea, where the accumulated freshwater strengthens the stratification. The water with sea ice melt is influenced by brine rejection and cooling accompanied by sea ice formation on its way to the Chukchi Abyssal Plain, resulting in a temperature minimum with $f_{\rm SIM} \approx 0$.

[34] The $S \approx 33$ temperature minimum water, which is PWW and spreads throughout the entire Canada Basin with a nutrient maximum [e.g., *Jones and Anderson*, 1986; *McLaughlin et al.*, 1996], has low potential vorticity east of the Chukchi Plateau. This indicates that the water influenced by winter convection over the northern Bering and Chukchi sea shelves [*Aagaard et al.*, 1981, 1985; *Schumacher et al.*, 1983; *Cavalieri and Martin*, 1994] mainly spreads east of the Chukchi Plateau. The $S \approx 33$ temperature minimum water also occurs west of the Chukchi Plateau, but the potential vorticity there is higher than to the east, suggesting that the volumetric injection of PWW is smaller to the west than to the east of the Chukchi Plateau.

[35] The $S \approx 32.5$ temperature maximum (salTmax) water over the Chukchi Abyssal Plain has been thought to originate in WCSW occupying the bulk of the Chukchi Sea shelf in summer [*Shimada et al.*, 2001; *Steele et al.*, 2004].

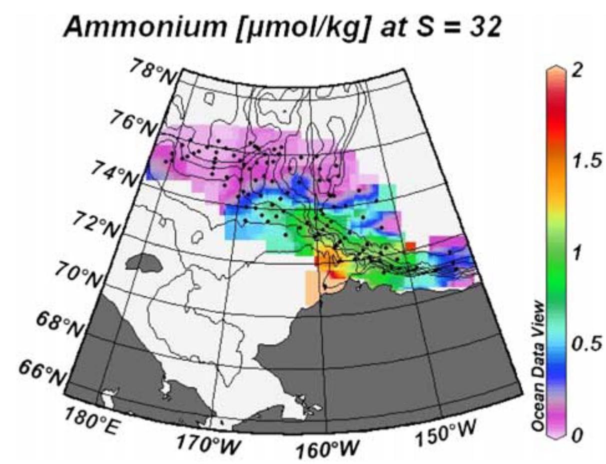

Figure 13. Ammonium at a surface of salinity of 32. Data from the Chukchi Sea Shelf (bottom depth <100 m) are excluded.

However, the *TS* relation at $S \approx 32.5$ over the Chukchi Abyssal Plain differs largely from that on the Chukchi Sea shelf. In addition, the relatively high potential vorticity at $S \approx 32.5$ over the Chukchi Abyssal Plain suggests that salTmax is not formed by a volumetric injection of summer shelf water. Therefore, salTmax represents not a substantial water mass, but a boundary between the two temperature minimum waters of $S \approx 32$ and 33. The coincidence of salTmax and the N** minimum also suggests that salTmax is a boundary of frTmin water derived from the Chukchi Sea shelf and PWW modified by the lower halocline water.

[36] The frTmin water supplies nutrients to the Chukchi Abyssal Plain, whereas PWW, which is the main carrier of nutrients and forms the nutrient maximum in the western Arctic Ocean, provides the largest amount of nutrients to the Canada Abyssal Plain. The nutrient supply by the frTmin water could maintain a prominent chlorophyll *a* maximum layer over the Chukchi Abyssal Plain. The combined effect of ECSW and frTmin water would be important for biological activity in the western Arctic Ocean. ECSW plays a role in the reduction of sea ice during summer [*Shimada et al.*, 2001, 2006], resulting in increased light intensity in the water column. The frTmin water supplies nutrients near the base of the euphotic zone, which is shallower than the PWW layer with the nutrient maximum, and the nutrients supplied by the frTmin water could be used effectively for biological activity.

[37] **Acknowledgments.** We gratefully acknowledge the captain, officers, and crew of the *R/V* Mirai, operated by Global Ocean Development, Inc. and the staff of Marine Works Japan, Ltd. for their skillful work onboard the ship and with data processing. Geographical maps and figures were created using ODV software (R. Schlitzer, Ocean Data View, 2003, http://www.awi-bremerhaven.de/GEO/ODV).

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